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Research Article

Enhancement of Compressive Strength in Cement Admixed Bangkok Clay with Glass Fiber and Bottom Ash for Eco-Friendly Functional Road Materials

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ABSTRACT

This article aims at the development of new eco-friendly functional road materials, examining the optimum mixing ratio of cement, bottom ash, glass fibers, and the mechanical properties of soil-cement subbase (pavement) materials. The optimum ratio of cement, bottom ash, and glass fibers was determined for the mixing of soil-cement as eco-friendly functional road materials. This study was carried out by using the unconfined compression test. All soil-cement samples were mixed at the liquid limit of 88%, with varying glass fiber content between 0.5, 1.0, 1.5, 2.0, and 2.5% by volume respectively. The glass fiber lengths were used 3, 6, and 12 mm. The OPC content was added between 2, 4, 6, 8, and 10%, respectively by dry weight. The bottom ash content was 5, 10, 15, 20, 25 and 30% by volume respectively. All soil-cement samples were cured for 7, 14, 28, 60 and 90 days. It was found that the optimum OPC soil-cement content mixture was around 8-10% according to ACI 230.1R-09 standard which requires OPC of 10-16% and the optimum fiber content was between 1.0 and 1.5%. The best UCS result for glass fiber length was 12mm. Finally, the optimum bottom ash content was 5-10%, and the recommended curing period should exceed 28-90 days.

1. Introduction

Bangkok's metropolis has faced severe problems of settlement and stability for many decades because it is situated on a soft clay layer. This clay soil is dense on the flood plains of the river basin from lower Chao Phraya to the mouth of the river which covers an area of approximately 15,000 km^2. A team of senior engineers [1] developed a Geographic Information System (GIS) by utilizing demarcations for soft clays from over 4,000 boreholes. The Gulf of Thailand's steadily increasing layers of thicker soft clay are typically found close to the coast. Decreases in thickness with distance to the north. In the Bangkok

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section, the thickness of the clay layer will be found around 10 - 20 m. The group of civil engineers [2] found that the geological characteristics of deep excavation in soft clay soils are sensitive to deformation and have little shear resistance to deep excavation, including the ability to predict the behavior of the support system and ground deformation with two case studies: the case of the Sukhumvit MRT station, a subway station on the Blue Line in Bangkok and Chicago subway station, Chicago, United States. In the case of Sukhumvit Station, it was noted that the contraction of the supporting floor slab, which is affected by heat shrinkage, will affect the deformation of the walls and the subsidence of the soil at every stage of station construction. Designers should pay attention to the relationship between brace design, thickness, and length. A case study on a pipe-jacking tunneling project that crosses the Bang Prakong River in Thailand was given by a group of geotechnical engineers [3]. The Klong Phra Ong Chaiya Nuchit and the Bang Pakong River were connected by this project, which belonged to the Thailand Irrigation Department. The method and procedure for building the tunnel that crosses the river at the level of a very soft clay layer using the pipe jacking method were explained in great detail. Additionally, the methods and procedures for building shafts for receiving pits and jacking pits using the sinking method were described. Due to its collapse, the jacking pit was turned around to become the receiving pit. The steel casing reconstructed this pit. The jet grouting approach was then used to improve the new jacking pit over the old receiving. Under 900 tons, the jacking force was under control. Along the tunnel line, the deviations were within ±60 mm in the horizontal direction and ±70 mm in the vertical direction. A group of researchers [4] studied the engineering properties of Bangkok clay is stable in a metastable condition as a result of structure. The total void ratio supported by the intrinsic fabric (e_R) and the additional void ratio resulting from the structure (e_S) is its void ratio or e. The void ratio at the liquid limit, e_L, is used to generate the intrinsic state line, which is expressed as e_R versus log σ'_v, where σ'_v is the effective vertical stress. In the post-yield state, e_s and σ'_v have an inverse relationship. The rise in effective vertical stress does not abolish the residual additional void ratio, or e_{sr}, which remains constant at roughly 0.20 for soft Bangkok clay and 0.12 for medium stiff Bangkok clay. The field yield stress and field compression curve can be evaluated based on these results and the ideal condition of zero compression at the pre-yield state. Since both the field yield stress and the undrained shear strength are structural reflections, they are immediately correlated. The permeability is not greatly impacted by the composition of the soil. The generalized state parameter, e/e_L, can be used to calculate the permeability of the clay in both structured and destructured states under the same void ratio. These findings lead to the development of an easy-to-use methodology for evaluating the engineering qualities of natural Bangkok clay. The feasibility study of steel reinforcement of polyethylene corrugated horizontal pipe for on-site underground water storage tanks and their applications in soil formation are clearly described [5]. The use of the bender element test, a non-destructive testing technique, to calculate the soft Bangkok clay samples' maximum shear modulus and measure the shear wave velocity [6]. This bender element method uses piezoelectric ceramic sensors to measure the shear wave velocity. The bender element test's specifics were described in depth. When the field test results and the laboratory bender element test data for the shear wave velocity are compared, it becomes clear that while the laboratory test data were conducted on small, potentially less stiff material, the field propagating waves pass along layers of higher stiffness. It was noted that the inversion calculation of the shear wave velocity in the field test is based on a linear elastic isotropic assumption which is not valid for the Bangkok subsoil.

Ordinary Portland Cement (OPC) is popularly used to improve the strength of Bangkok soft clay. The deep mixing method, also known as soil-cement column, is a method of improving the soil for Bangkok clay to increase its weight-bearing capacity and reduce subsidence by studying the strength development factors of cement mixed with Bangkok clay. It was found that the clay-water/cement mixture ratio w_c/C was an important parameter controlling the development of soil-cement strength and it was also found that the liquidity index varied between 1 and 2 depending on this parameter and Abram's law [7]. A study of the strength development of Bangkok soft clay mixed with Type 1 Portland cement at the rate of 20% by weight and cured for 3, 7, 14, and 28 days by using the Bender Element Test and Unconfined Compressive Stress test (UCS) was found that the tests using the above methods consistently confirm that the curing time increases the strength of the soil-cement, will develop higher strength [8]. A team of engineers [9] conducted studies to ascertain the initial shear modulus and unconfined compressive strength of Bangkok mild clay that had been enhanced by fly ash (FA) and ordinary Portland cement (OPC). While FA serves as a sustainable substitute for cement because it is a waste byproduct of Thailand's Mae

Moh power plant, cement is used to stabilize Bangkok's fragile clay. Bangkok soft clay is combined with 0–30% by weight of FA replacement and 20% by weight of OPC. The initial shear modulus, which is suitable for cyclically and continuously curing time modeling, is ascertained from shear wave velocity measured by a self-developed non-destructive bender element after curing for 7, 14, 28, and 90 days. The destructive unconfined compressive strength (UCS) tests are another method used to measure the strength development of tested clay samples for comparison and result validation. According to the study, the ideal FA replacement at 90 days is 20% according to the initial shear modulus and 15% according to the unconfined compressive strength. Furthermore, as the curing period increases, so does the initial shear modulus and the unconfined compressive strength. The early-age normalized unconfined compressive strength is determined to be 0.09, and the connection between the normalized unconfined compressive strength and the curing time is found to be naturally logarithmic with the increasing rate at 0.3433. The bender element test's limitation is discovered through comparison with a study; despite their benefits for constitutive modeling in various computations (such as the finite element method, FEM, dynamic analysis of soil property, etc.), they can only determine small strain quantities in terms of G_0 or E. This study's normalized shear modulus and unconfined compressive strength connection are consistent with previous research, while there is considerable variation because of the various compositions, types of clay, cement concentration, and stabilizers. Therefore, more research on this disparity is advised. Alternatively, the pozzolan is a cement replacement material. Which is a by-product of the iron and steel industry. It will be found that Ground Granulated Blast Furnace Slag (GGBS) has chemical characteristics similar to cement. Pozzolanic materials rely on secondary reactions after cement hydration. It reacts with free calcium hydroxide to form the calcium silicate hydrate (C-S-H) phase, which is an important factor in strengthening concrete. As a result, pozzolanic concrete has long-term strength development of up to 91 days and depleted calcium hydroxide levels. Pozzolanic concrete therefore has better sulfate resistance [10]. Bottom ash (BA) left over from the coal burning industry. This would have originally been destined for landfill instead of being used in the concrete industry. There is research that studies the use of coal bottom ash as a partial substitute for cement and the properties of high-strength concrete. Pozzolanic properties of coal bottom ash by grinding until 95 ± 1 wt.% of the size passed, through sieve number 325 and had the same fineness to evaluate Pozzolanic reaction of BA floors, cement substitution results in ASTM C618 [11]. Engineering industries prioritize sustainable and eco-friendly products for their recyclability, availability, and property variability. Developing eco-friendly materials is a crucial part of the sustainability efforts [12]. Despite significant efforts to develop innovative materials and manufacturing techniques, the wide range of engineering applications for eco-friendly sustainable composites remains limited due to issues with material compatibility, mechanical properties, and post-processing procedures [13]. And, the stricter laws are making manufacturing and production more and more challenging. Innovative materials allow businesses to comply with regulations without sacrificing performance [14].

In 2023, Thailand's municipal solid waste (MSW) production was 26.95 million tons compared to 25.70 million tons in 2022, representing a 4.64% increase that was likely driven by increasing urbanization (PCD, 2023)[15]. On the other hand, MSW is a possible substitute energy source. The alternative energy development plan [16], policy, and target set by the Thai government encourage the use of 495 ktoe of MSW for thermal energy by 2037. The utilization of refuse-derived fuel (RDF) for thermal energy in 2023 fell short of the 29% target [17]. In Thailand, RDF is a fuel that is widely used in the cement industry. Excavating and processing landfilled waste to produce recyclable materials, soil-like materials, and RDF is known as landfill mining. Systematic planning is the key to making landfill mining effective [18]. However, the by-products created when municipal solid waste is burned in solid waste combustor facilities are fly ash (FA) and bottom ash (BA) from MSW combustor facilities. And, the most significant method for getting rid of the growing amounts of MSW produced in Thailand is incineration, which has surpassed mining in landfills [19]. The ash that falls to the bottom of the MSW combustor as fallen clinker is known as BA, and the ash that flows up the chimney is known as FA. Comparable in size to fine sand up to gravel, the particles of BA are larger than those of FA and come in a variety of shapes. According to ASTM C618 standards, silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), and ferric oxide (Fe_2O_3) make up the majority of the chemical composition of BA. These materials are categorized as pozzolanic materials ASTM C618. And, FA was more frequently used as a stabilizer in soil stabilization than BA because of its high SiO_2 content, which is advantageous for the cement hydration reaction process. FA also has very fine particles with a higher surface particle count, which helps to speed up the hydration reaction [20]. FA also possesses pozzolanic qualities, which include high silica and alumina content. When pozzolanic material, lime, and water are combined, a reaction and bond are formed. Consequently, to raise the soil's carrying capacity, fly ash can be added to clay soil as a stabilizing substance [21]. Because of pozzolan's influence or FA's inherent hardening qualities brought on by compaction and moisture levels, mixing fly ash with soil material will cause a cementation bonding process. According to earlier research, the advantages of using fly ash as a soil stabilizing agent and concrete material include a decrease in the need for water, an increase in cohesion, a decrease in soil permeability and shrinkage, and stronger concrete [22]. BA and ground bottom ash (GBA) are being studied for more beneficial uses. Finding the impact of BA and GBA and cement properties that make Bangkok clay stronger and that consideration includes the initial water content and clay/binder mix ratio. Cement/BA ratio and curing time Unconfined Compressive Strength test (UCS) Scanning Electron Microscopy (SEM) evaluation was performed. As for BA mixed in 60 clay/40 binder, it has sufficient strength to pass the requirements of the Thailand Department of Highways (DOH) [23] for cement column materials [24]. In addition to using BA from coal to help reduce environmental problems, there is also BA that comes from burning community waste. Mixing bottom ash of a power plant in Rayong Province with OPC and Latex. To be an alternative material for road works tests revealed an optimal mixture of BA to OPC ratios of 95:5 and 93:7, respectively, with Para Rubber Latex (PRL) 6% as a mixture and BA–OPC–PRL having a low risk of slipping [25]. Therefore, using FA and BA as additives in soil stabilization can be ideal alternatives for environmental and civil engineering.

Natural and synthetic fibers have been used for new innovative eco-friendly materials in engineering applications. The primary advantages of the environment, safety, cost, and competition in a range of engineering challenges have led to their increased importance. Using the distinct qualities and functionalities of multiple materials in lightweight structures while increasing the efficiency of each material is a successful strategy that hybrid systems aim to implement. Fiber-reinforced polymer (FRP) composites and other lightweight materials have received a lot of attention recently [26]. For example, the addition of multi-walled carbon nanotubes (MWCNTs) improves the properties of polymer composite materials while adding very little weight but this helps to improve the interfacial bonding strength between the resin and the nanoparticles. This work produced adequate results in fields where greater mechanical, tribological, and morphological properties were expected, such as the structural, aerospace, and automobile industries [27]. Natural fibers like kenaf, sisal, pineapple, bamboo, and banana have been discussed. Also, a lot of thought has gone into the origins and characteristics of each of these natural fibers. These natural fibers have been investigated by researchers as a potential reinforcement for various composites. Similarly, these five natural fibers' mechanical characteristics and uses are also covered. Thus, natural fibers are being used in a variety of commercial sectors to create eco-friendly products that will eventually replace synthetic fibers with more productive and cost-effective options [28]. So, the need to develop natural fiber-reinforced polymer composites has arisen from the high cost and environmental hazard of artificial fibers such as carbon and kevlar. The risk to the environment has decreased when natural fibers are used as reinforcement. According to the study, jute has the highest Young's modulus, silk has the highest elongation at break, and abaca has the highest tensile strength. This indicates that natural fibers, which are safe, renewable, and environmentally friendly sources of fiber, will be widely utilized in composite materials in the years to come [29]. Among its composites, natural fibers stand out for being biodegradable. Natural fibers can be separated at less expensive rates and are readily available. When it comes to handling, natural fibers are easier than other synthetic fibers. Lingo cellulosic fibers containing cellulose, hemicelluloses, pectin, waxes, and lignin are called plant fibers. There are several uses for natural fibers, including continuous and randomly oriented applications. In the non-wooden industry, lemon grass can serve as a substitute. Lemongrass has a higher cellulose percentage and a lower lignin content. So, the strong structure of the fiber is a result of hydrogen bonding between fibers [30]. When it comes to natural fibers, abaca is a strong rival for use in polymer composite reinforcement. The findings show that abaca is especially adaptable and can be used in a variety of industries, with different matrices, and in hybrid composites made of different types of fibers [31]. Moreover, the results showed that the morphological characterization of the neat epoxy was enhanced by the inclusion of abaca fibers in the composite materials. When compared to other composite specimens, scanning electron microscope (SEM) micrographs of 25% of the abaca fiber-epoxy composites demonstrated superior worn properties [32]. The characterization of their applications in 3D and 4D printing is also included, as the production of green composites from natural fibers is a promising field. The necessity of selecting a more environmentally friendly option, such as a natural fiber, as opposed to a synthetic fiber that is not biodegradable and will inevitably pose risks to the environment and its uses to enhance eco-friendly goods and swap out synthetic fibers for more economical and efficient options [33]. Natural fibers are not only found in plants but also in animals. Hybrid sandwiched composites of duck feather fiber (DFF) and jute fiber (JF) reinforced polymer are fabricated and their properties are experimentally investigated. The investigation's findings can be successfully applied to a variety of industrial applications, as it was found that three layers of DFF and JF composites performed well mechanically when compared to two layers of composites [34]. One good alternative to the synthetic forms is thought to be chicken feather fiber or CFF. As a by-product of raising chickens, CFF is challenging to analyze, handle, and post-process due to the lack of established extraction techniques. Nonetheless, the CFF is an intriguing class of fibers with a wide range of potential applications due to its relative abundance and complementary qualities for the development of environmentally friendly, sustainable products are thoroughly examined, along with some disparities in the material's stated qualities [35]. Because of its widespread industrial use, natural fiber eventually ceases to be considered an environmental waste. So, various levels of criteria were applied to the classification of natural fibers. When engineers are choosing natural fiber composites based on their practical applications, this criteria acts as a fundamental tool. Especially in areas like chemical resistance, impact resistance, and, occasionally, process cost [36]. Nevertheless, glass fiber is a filler that is lighter stronger, and economical which is offered for use in reinforcing Glass Fiber-Reinforced (GFR) applications in aerospace, and construction and it is also resistant to corrosion. Also, the glass fiber must be selected appropriately for reinforcement. The direction of the glass fiber towards the reinforcement. Reinforcing the fibers into a mesh can increase shear strength and hardness. Glass fibers also help fiber-reinforced materials to resist deformation, which must be taken into account for density and location of reinforcement [37-38]. Study of deformation of glass fiber reinforced specimens between clay and sand soils by adding glass fiber size 0.15 mm. It was noted that the glass fiber should length not exceeding 30 mm, was suitable for clay and sandy soils from 0 - 4%, and was tested using combined undrained and combined triaxial tests. It was found that the most suitable glass fiber reinforcement was 0.75% in clay soil and 3% in sandy soil with the optimum fiber length being 20 mm. The fibers contributed to an increase in the friction angle [39-40].

An engineering team [41] reports on a laboratory analysis of the cementeclay admixture's strength behavior enhanced by polypropylene fiber. Since waste polymer textile bags are bad for the environment, it is critical to find sustainable ways to reuse them. Using these waste polymer textile bags in compacted pavement base/subbase projects is an innovative way to recycle them and improve soft soil. A series of laboratory oratory investigations are carried out on fiber-reinforced cement-improved soft Shanghai clay to confirm the efficacy of fiber bundles employed in soil mixing. Polypropylene monofilament fiber and fiber bundles separated from polymer textile bags were the two types of polymer fibers used in the studies. After the fiberesoilecement admixture specimens were cured for a while, the tests were performed utilizing the unconfined compressive strength (UCS) test. The findings demonstrate that adding fiber can greatly increase the Shanghai clay treated with cement's strength and ductility. The content and length of the fiber have an impact on the UCS of the fiberesoilecement admixture. At 0.5% fiber concentration, the two types of fiber-reinforced cement clay reached their maximum strength. If the fiber content keeps rising, UCS will gradually reverse. The performance difference between the fiber bundles and the polypropylene fiber is less than 5%. These findings suggest a new method for handling waste polymer textile bags: using the fiber bundles that separate from the polymer bags as reinforcement when mixing soil. A group of researchers [42] examined how new high-strength polyethylene fibers affect the behavior of concrete with added Bangkok clay cement in terms of unconfined compressive strength (UCS). Ordinary Portland Cement (OPC) was mixed with Bangkok clay samples at weight ratios of 2, 4, 6, 8, and 10% after the clay samples were processed to a liquid limit of 88%. Polyethylene fibers were also added at volume ratios of 0.5, 1.0, 1.5, 2.0, and 2.5%. These materials underwent an unconfined compressive test after being cured for 7, 14, and 28 days. Based on test results, the ideal cement content was found to be 8% by weight; a recommended polyethylene fiber content is 1% by volume.

This study aims at the development of new eco-friendly functional road materials, examining the optimum mixing ratio of cement, bottom ash, and glass fibers and the mechanical properties of soil-cement subbase (pavement) materials. Furthermore, workability, physical characteristics, and mechanical behavior during road construction are investigated by the research in relation to bottom ash and glass fibers. Glass fibers and bottom ash were utilized as a subbase in place of cement to reduce expenses. Consequently, Portland cement was replaced with soil-cement mixtures and glass fibers.

2. Materials and Preparation

2.1. Bangkok Clay

The Bangkok clay used for testing was soil from the Purple Line subway project south of Vajira Hospital Station, with a depth of 10-12 meters as seen in Fig. 1. It was taken to the laboratory of King Mongkut's University of Technology North Bangkok (KMUTNB), Bangkok Campus. It was found that the basic properties of the chemical composition of the samples taken for testing are shown in Table 1. It was found that the natural water content was in the range of 81% and the liquidity index of the clay was close to the surface level. It is approximately 1.0 but decreases with depth as shown in Table 3. As per ASTM D 4318-93[43], the liquid limit of 88% and the plastic limit of 34% were established for Bangkok clay. Using ASTM D 4253[44], the specific gravity of 2.68 for Bangkok clay was determined. ASTM D 2216-19 [45] invested in Bangkok clay with a moisture content of 81%. As of late, ASTM D 7263-21[46] tested Bangkok clay, giving a unit weight of 1.47 t/m^3.

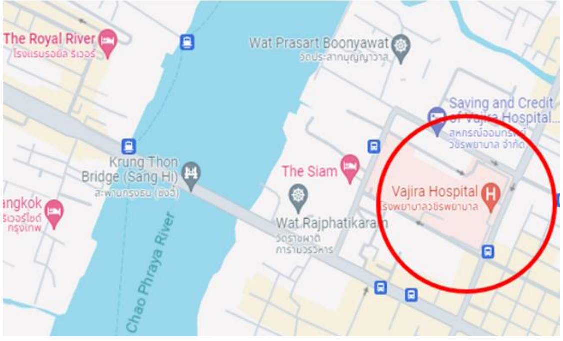

Fig. 1. The Purple Line subway project south of Vajira Hospital Station

Table 1. Chemical compositions of Bangkok clay and Portland cement

Comp.	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3
Bangkok clay (%)	62.50	18.40	8.49	1.07	2.35	1.86
OPC (%)	20.90	4.76	3.41	65.41	1.25	2.71

2.2. Portland Cement and Bottom Ash

Ordinary Portland Cement (OPC) is the main ingredient in Bangkok clay to stabilize Bangkok clay samples. The main components of Portland cement are shown in Table 1. Its specific gravity is approximately equal to 3.14. In addition, Bottom Ash (BA) is a by-product obtained from burning waste from power plants in Rayong Province. which is in the eastern region of Thailand. Take the bottom ash through sieving with sieves No. 3/8, 4, 10, 20, 40, 100 and 200. Set a time period of 10 minutes per round as shown in Fig. 2. Separation of bottom ash using a sieve, weigh and write down the values, as shown in Fig. 3. Choose to use bottom ash that has passed through sieve No. 100 to find the specific gravity value as shown in Fig. 4. The specific gravity of the bottom ash of Tanjung bin was determined by researchers [47]. The bottom ash has a value in the range of 1.88 - 2.44 Mg/m^3. Testing for relative density according to ASTM D4253 and ASTM D4254 [48] is recommended for soils with silt or clay fineness less than 15 % and is suitable for determining the density of ash lower than the relative density according to ASTM D4253. The result of the bottom ash density test of a power plant in Rayong Province was 2.21, with the chemical composition of BA shown in Table 2.

Fig. 2. Separation of bottom ash using a sieve

Fig. 3. Bottom ash (BA) that can be separated into different sizes

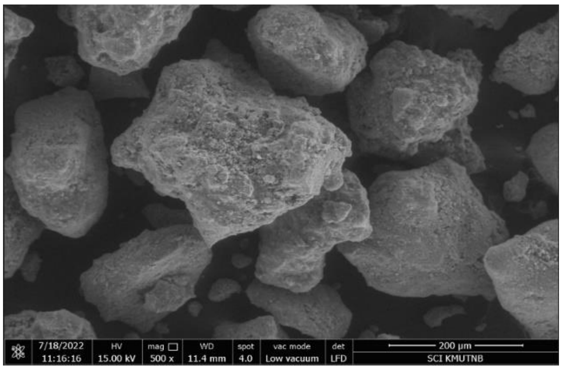

Fig. 4. Bottom ash (BA) from Refuse Derived Fuel (RDF)

Table 2. Chemical compositions of Bottom ash

Comp.	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3
BA (%)	7.94	1.48	32.56	47.52	4.56	0.53

Table 3. Properties of Bangkok soft clay

Liquid limit (%)	Plastic limit (%)	UCS (kPa)	Specific gravity	Moisture content (%)	Unit weight (t/m^3)
88	34	1.48	2.68	81	1.47

2.3.Glass Fiber

The glass fibers used in this research were manufactured by Owens Corning serial Advantex cs 979-14 fibers with lengths of 3, 6, and 12 mm as shown in Fig. 5.

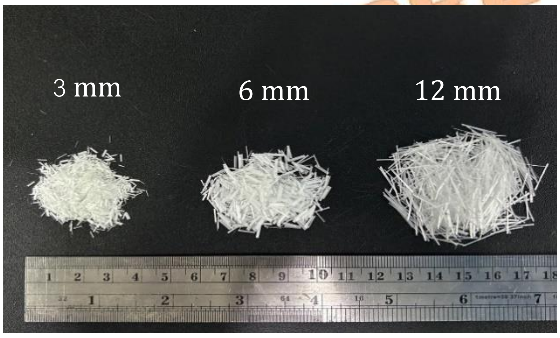

Fig. 5. Glass fiber

2.4. Preparing Soil-Cement

In preparing all Bangkok clay samples, the Ordinary Portland Cement (OPC) at various contents 2, 4, 6, 8, and 10% by dry weight is mixed with water at the liquid limit of 88%. The bottom ash ratio is 5, 10, 15, 20, 25, and 30% by dry weight and reinforced with glass fiber ratios of 0.5, 1.0, 1.5, 2.0, and 2.5% with length sizes of 3, 6, and 12 mm according to the mixing ratio as shown in Table 4. Then all samples were cured for 7, 14, 28, 60, and 90 days. Each individual test samples at a ratio of 5 samples per 1 set, which were 280 samples in total.

3. Experiment

The test method for investigating the strength development was used the unconfined compressive strength (UCS) according to ASTM D1633–17 [49] as seen in Fig. 6. All soil-cement samples were prepared with the PVC cylindrical mold with 50 mm in diameter and 100 mm in height. Then, all these samples were wrapped with plastic membrane to protect against moisture loss and cured for 7, 14, 28, 60, and 90 days. The applied loads were measured using a 50 kN load cell. An electric motor controlled the compression rate of 2 mm/min, and the test ended at a net displacement of 15 % specimen height or failure by using averaged displacement from two LVDTs. All tests used the averaged data of 3 samples within 10 % error.

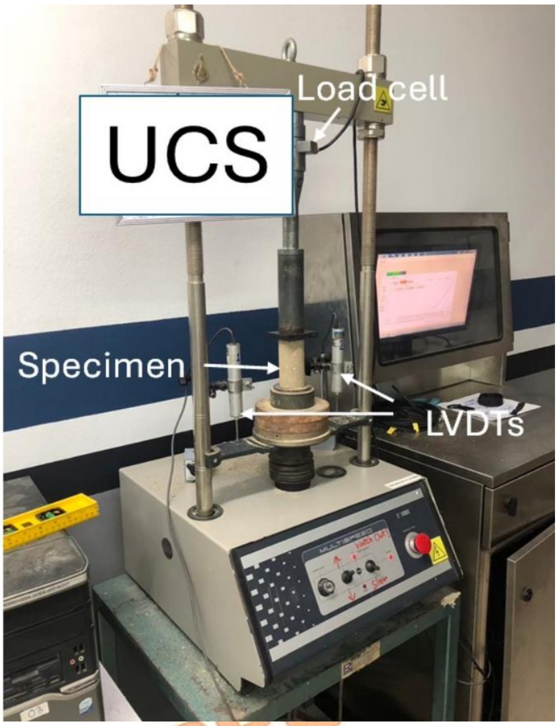

Fig. 6. Unconfined compressive strength test

4. Test Results

4.1. Effect of Cement Content

The effect of cement content on the strength development is shown in Fig. 7 as a bar chart, comparing the unconfined compressive strength (UCS) development with different mixtures of the OPC content in group A. The curing time was set at 28 days. It was found that in general, the UCS increased with increasing the OPC content. The optimum OPC mixing was around 8-10%, showing the UCS of 700.03 and 702.48 kPa, respectively which was as good as the Shanghai clay data [41] and was a sufficient proportion and passed the standard for subgrade material according to ACI 230.1R-09 [50] (according to

Table 4.1, category A-7, MH, OH group, cement is between 10-16%) and DOH standard in Thailand [23].

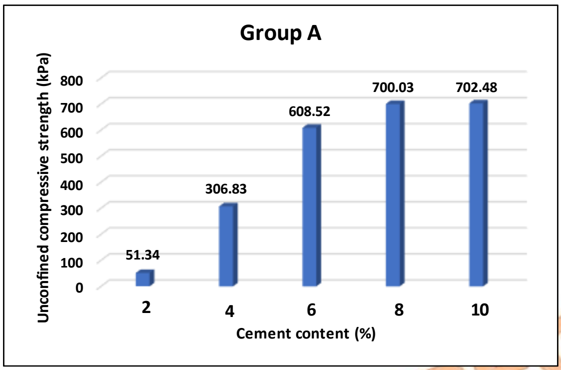

Fig. 7. Bar chart showing the relationship between UCS and cement ratio

4.2. Effect of Bottom Ash Content

The effect of bottom ash content on the strength development of soil-cement with varying the ratio of bottom ash (BA) for group B, the amount of glass fibers, and the size of glass fibers were fixed as same as group A. Fig. 8 depicts a bar chart showing the comparison of the development of unconfined compressive strength (UCS) with the cement ratio by adding bottom ash at a ratio of 20% and adding glass fibers with a length of 6 mm at a ratio of 1.0% using a curing time of 28 days. It was noted that the UCS results increase with an increasing amount of the BA content. The appropriate OPC ratio for increasing UCS according to ACI 230.1R-09 [50] (according to Table 4.1, category A-7, MH, OH group, cement is between 10-16%) is 10%, resulting the unconfined compressive strength of 447.57 kPa and was considering the OPC ratio of 8% which has an unconfined compressive strength of 321.88 kPa and passed the standard for subgrade material. It was an interesting amount of OPC when it will be considered together with the addition of BA.

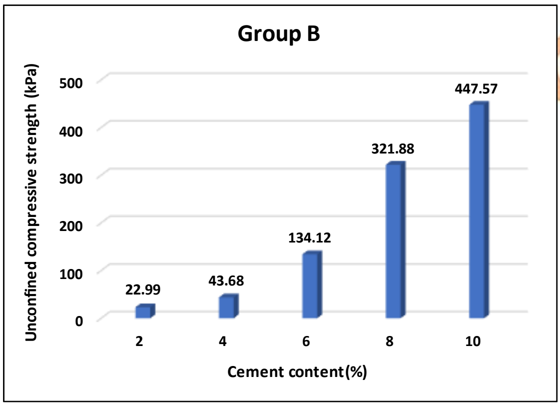

Fig. 8. Bar chart showing the relationship between UCS cement ratio and bottom ash

4.3. Effect of Glass Fiber Content

The effect of glass fiber content on UCS development with fixing the proportion of cement, bottom ash, and glass fiber length. Fig. 9 expressed in a bar chart, shows the comparison of the development of unconfined compressive strength (UCS) with the glass fiber ratio by adding cement at a ratio of 8%, bottom ash at a ratio of 20%, and using glass fiber with a length of 6 mm, the curing time was 28 days. It was noted that the optimum amount of glass fiber ratio of 1.5% showed the maximum UCS result of 328.78 kPa which was less than the Shanghai clay results [41] because BA was added into the Bangkok clay-cement mixing. Adding glass fiber content did not result in the increment of UCS but it will cause the UCS data to decrease. Therefore, mixing glass fiber in a large ratio did not result in an increase in compressive strength as well.

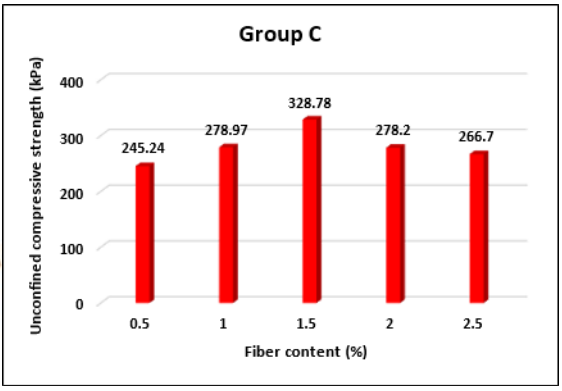

Fig.9. Bar chart showing the relationship between UCS and glass fiber volume ratio

4.4. Effect of Glass Fiber Length

The effect of glass fiber length was investigated. The glass fiber lengths of 3, 6, and 12 mm were used and fix the amount of cement, bottom ash, and glass fiber ratio. Fig. 10 shows the comparison of UCS with varied glass fiber lengths. By adding cement at a ratio of 8%, bottom ash at a ratio of 20%, and glass fiber at a ratio of 1.0% using a curing time of 28 days. It was observed that the UCS results were about 240-260 kPa. However, the maximum UCS value was found with the 12 mm in glass fiber length at 259.04 kPa which was also less than the Shanghai clay results [41] because BA was added into the Bangkok clay-cement mixing. Moreover, there was a tendency to increase the UCS data by increasing the glass fiber length.

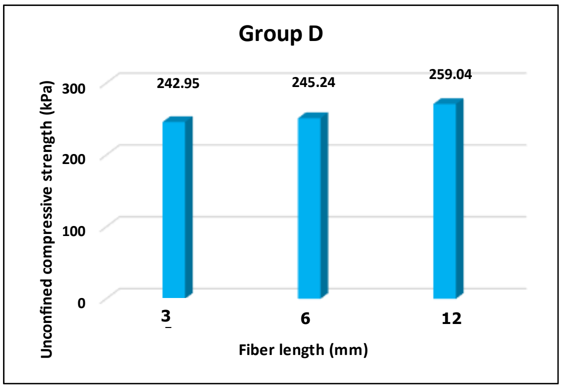

Fig. 10. Bar chart showing the relationship between UCS and glass fiber length4.5. Effect of cement content

4.5. Effect of BA Content and Aging

The aging effect on the variation of BA content between 5-30% was studied by fixing the cement content, glass fiber content, and glass fiber length ratio. Fig. 11 describes a bar chart showing a comparison of the development of unconfined compressive strength (UCS) with the bottom ash ratio. By adding cement at a ratio of 10% and using glass fiber with a length of 6 mm at a ratio of 1.0% using a curing time of 7, 14, 28, 60, and 90 days. It was found that the UCS developed by changing the ratio of bottom ash in the mixture with 5 different mixtures and curing periods 7, 14, 28, 60, and 90 days. The curing time of 90 days gave the highest UCS values and higher than UCS data at 28 days. The ratio that has the highest UCS compressive strength of the bottom ash ratio of 5% and 10%, which is 457.34, and 437.61 kPa, respectively, at a curing time of 90 days. The UCS compressive strength was similar to that of using OPC 10% of 447.57 kPa and it was found that at 5% and 10%, the UCS compressive strength was approximately 320.61, and 296.59 kPa respectively, which gave a similar value to using OPC at 10% which was 321.88 kPa. The bottom ash should be added as much as possible as a replacement material for OPC at 10% with a curing time ranging from 28 - 90 days to meet the ACI 230.1R-09 standard [50] (according to Table 4.1 Category A-7, MH, OH group, cement is between 10-16).

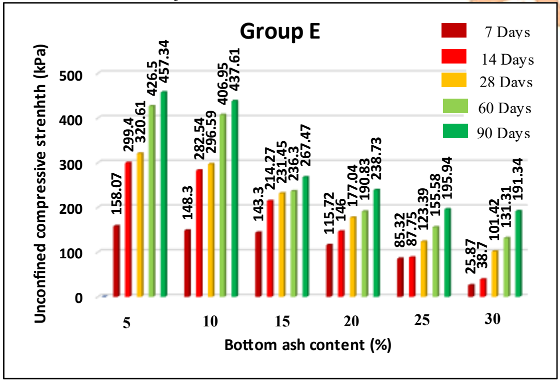

Fig.11. Bar chart showing the relationship between UCS and BA ratio at incubation periods of 7, 14, 28, 60, and 90 days

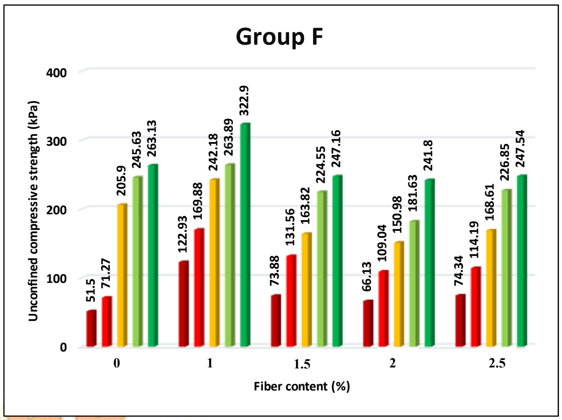

Fig.12. Bar chart showing the relationship between UCS and glass fiber volume ratio at incubation periods of 7, 14, 28, 60, and 90 days

4.6. Effect of Glass Fiber Content and Aging

The effect of glass fiber content on force development at the same ratio of cement, bottom ash, and glass fiber length. Fig. 12 was a bar chart showing the comparison of unconfined compressive strength (UCS) development with glass fiber ratio. By adding cement at a ratio of 8%, bottom ash at a ratio of 20%, and glass fiber with a length of 6.00 mm, curing times were 7, 14, 28, 60, and 90 days. Tests showed that the compressive strength developed by changing the fiber ratio glass in the mixture with five different curing periods: 7, 14, 28, 60, and 90 days. The maximum UCS compressive strength was found at 90 days. The UCS compressive strength was 322.90 kPa and it was noted that the glass fiber ratio that gave the UCS compressive strength was a glass fiber content of 1.0% which was a bit higher than the finding of 0.5% for Shanghai clay data [41]. Therefore, mixing a glass fiber ratio of 1.0% was appropriate to develop the best compressive strength.

4.7. SEM Image Analysis

Figure 13 shows the SEM image of Bangkok clay, BA, glass fiber, and cement. The SEM image 70x expansion shows that the BA is mixed homogeneously with the glass fiber and the soil-cement matrix. It is associated with friction in a proportional way to the length of the glass fibers used to show how composite materials may be improved, and it also has an impact on how soil cement's strength qualities can be improved. The sample demonstrates the composite material's adhesion and glass fiber dispersion. The strength grows with the length of the glass fibers, and they can bind to one another. Fig. 14 depicts the SEM image 400x out of the red dot circle in Fig. 13, showing the bonding between the glass fiber and the soil-cement matrix.

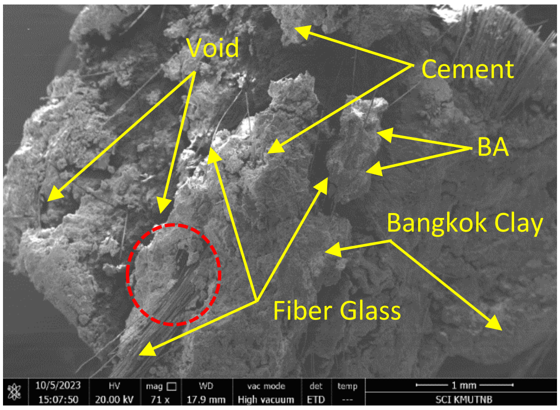

Fig. 13. SEM image 70x of soil-cement with glass fibers

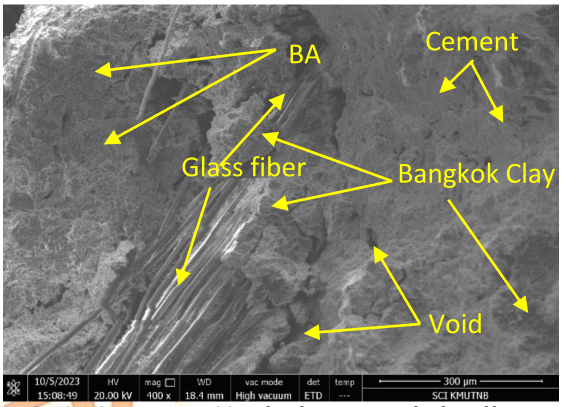

Fig. 14. SEM image 400x of soil-cement with glass fibers

Table 4. Mixing proportions of Bangkok clay samples

Serial No.	Cement Content (%)	Cement Weight (g)	BA Content (%)	BA Content (g)	Fiber Content (%)	Fiber Content (g)	Fiber Length (mm)	Moisture Content (%)	Curing Time (day)
A1	2	3.19	0	0	0	0	0	88	28
A2	4	6.38	0	0	0	0	0	88	28
A3	6	9.57	0	0	0	0	0	88	28
A4	8	12.77	0	0	0	0	0	88	28
A5	10	15.96	0	0	0	0	0	88	28
B1	2	3.19	20	0.80	1.0	4.93	6	88	28
B2	4	6.38	20	1.60	1.0	4.93	6	88	28
B3	6	9.57	20	2.40	1.0	4.93	6	88	28
B4	8	12.77	20	3.19	1.0	4.93	6	88	28
B5	10	15.96	20	3.99	1.0	4.93	6	88	28
C1	8	12.77	20	3.19	0.5	2.47	6	88	28
C2	8	12.77	20	3.19	1.0	4.93	6	88	28
C3	8	12.77	20	3.19	1.5	7.40	6	88	28
C4	8	12.77	20	3.19	2.0	9.86	6	88	28
C5	8	12.77	20	3.19	2.5	12.33	6	88	28
D1	8	12.77	20	3.19	1.0	4.93	3	88	28
D2	8	12.77	20	3.19	1.0	4.93	6	88	28
D3	8	12.77	20	3.19	1.0	4.93	12	88	28
E1	10	15.16	5	0.80	1.0	4.93	6	88	7;14;28;60;90
E2	10	14.36	10	1.60	1.0	4.93	6	88	7;14;28;60;90
E3	10	13.56	15	2.40	1.0	4.93	6	88	7;14;28;60;90
E4	10	12.77	20	3.19	1.0	4.93	6	88	7;14;28;60;90
E5	10	11.97	25	3.99	1.0	4.93	6	88	7;14;28;60;90
E6	10	11.17	30	4.79	1.0	4.93	6	88	7;14;28;60;90
F1	8	12.77	20	3.19	0.5	2.47	6	88	7;14;28;60;90
F2	8	12.77	20	3.19	1.0	4.93	6	88	7;14;28;60;90
F3	8	12.77	20	3.19	1.5	7.40	6	88	7;14;28;60;90
F4	8	12.77	20	3.19	2.0	9.86	6	88	7;14;28;60;90
F5	8	12.77	20	3.19	2.5	12.33	6	88	7;14;28;60;90

5. Conclusions

This study aims at the development of new eco-friendly functional road materials, examining the optimum mixing ratio of cement, bottom ash, and glass fibers and the mechanical properties of Bangkok clay-cement subbase (pavement) materials. The following conclusions are reached in light of the research findings:

- It was recommended to use the OPC in the Bangkok clay mixing at least 8% in order to reach the DOH standard for Thailand [23].
- It was found that glass fiber content should be added around 1-1.5% into the soil-cement mixing in order to reach the DOH standard for Thailand [23].
- It was observed that the maximum UCS value was found with the 12 mm glass fiber length. There was a tendency to increase the UCS data with increasing the glass fiber length.
- It was discovered that the bottom ash (BA) should be added into the soil-cement mixing around 5-10% replacement of OPC.
- It was confirmed that there was a bonding between the glass fiber and soil-cement matrix, resulting in an increase of UCS with increasing fiber content up to 1-1.5% and increasing glass fiber length.

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